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# A process systems approach for detailed rail planning and scheduling applications

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ABSTRACT

Value chain integration is an ongoing challenge: while computing power has improved, there is little modeling consistency across the system. This paper bridges this gap by proposing a novel formulation for train scheduling, a linking element of value chains, using the Unit-Operation-Port-State Superstructure (UOPSS). Train scheduling is a challenging problem: rail lines can be hundreds of kilometers long with train crossing strategies that are based on a train station level, while also requiring results with a minute-time scale resolution. In mixed-use rail systems with limited passing loop infrastructure, trains have different passing priorities and lengths, thus differing in their ability to use passing loops. The proposed model is the basis of the Hatch Rail Optimizer (HRO) software. In addition to small case studies, the power of HRO is demonstrated through a practical case study involving a 370 km rail corridor with five different train sizes over a week-long scheduling horizon.

## 1. Introduction

### 1.1. Value chain integration

Value chain operations benefit significantly from integrated modeling and optimization. In spite of this, there are many reasons why most value chains are decentralized and cannot be fully integrated into a single model (Kelly and Zyngier, 2008). Detailed fully-centralized models of entire value chains can be very difficult to maintain, thus compromising their long-term usage, and may not even be solvable with available computing power. In addition, some information cannot be shared across different stakeholders in the value chain. Since full centralization is typically not achievable, the authors suggested that adding a coordination model that spans across all stakeholder systems is key to having more efficient operations across the entire value chain.

Since a value chain coordination model spanning the entire system leads to more efficient operations, a key integration enabler is the ability to represent the entire system (from suppliers to consumers) in a unified modeling framework. This does not imply having to represent the detailed stakeholder submodels using the same framework: it is sufficient for each stakeholder to receive its production/processing targets from the (unified) coordination model, since the latter considers integrated system objectives.

There are several strategies for representing decision-making systems in the literature especially in the area of Process Systems Engineering, such as State-Task Network (STN, Kondili et al., 1993), Resource-Task Network (RTN, Pantelides, 1994) and Unit-Operation-Port-State Superstructure (UOPSS, Kelly, 2005; Zyngier and Kelly, 2009). In this paper, UOPSS was selected due to its modeling flexibility, intuitive nature and the tightness of its constraints, in addition to seamlessly managing limited connectivity between system elements.

UOPSS was originally developed for application in the Process Industries. Nevertheless, its flexible modeling structure provides a solid basis for modeling any supply chain system, including rail operations. A very important benefit of adopting UOPSS as a modeling framework is that the resulting rail scheduling models may be easily expanded with adjacent elements of the value chain, such as mining operations, production facilities, warehouses, material stockpiles, container terminals, etc., thus enabling true value chain integration.

### 1.2. Rail system description

Rail systems were introduced in the nineteenth century and have played a key role in transporting people and goods across vast territories ever since. To this day, they remain a critical component of many value chains. More sophisticated strategies for planning, scheduling and controlling railcars through the system have been increasingly required given the higher utilization of rail lines and

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**Nomenclature**

*Indices*

| | |
|---|---|
| $d$ | Travel directions |
| $m$ | Train types |
| $pl$ | Passing loops |
| $s$ | Sections |
| $t$ | Time |

*Parameters*

| | |
|---|---|
| $InvPLmax_{pl,m,d}$ | Maximum inventory of trains of type $m$ in passing loop $pl$ in direction $d$. |
| $UT_{s,m,d}$ | Travel time of train $m$ through section $s$ in direction $d$. |

*Continuous Variables*

| | |
|---|---|
| $FPLi_{pl,m,d,t}$ | Flow of train $m$ into passing loop $pl$ in direction $d$ in time $t$. |
| $FPLo_{pl,m,d,t}$ | Flow of train $m$ out of passing loop $pl$ in direction $d$ in time $t$. |
| $InvPL_{pl,m,d,t}$ | Inventory of trains $m$ in passing loop $pl$ in direction $d$ in time $t$. |
| $sd_{s,m,d,t}$ | Shutdown of section $s$ running train $m$ in direction $d$ in time $t$. |
| $y_{s,m,d,t}$ | Setup of section $s$ running train $m$ in direction $d$ in time $t$. |

*Binary Variables*

| | |
|---|---|
| $su_{s,m,d,t}$ | Startup of section $s$ running train $m$ in direction d in time $t$. |
| $yL_{ls,m,d,t}$ | Setup of large section $ls$ with train $m$ in direction $d$ in time $t$. |

increased pressure on reducing emissions, capital and operating costs of rail systems.

An illustration of a small section of a single train track ("single-line") rail system is shown in Fig. 1. The track between train stations is called a "Section". "Passing loops" are track segments that allow trains to pass each other on single tracks.

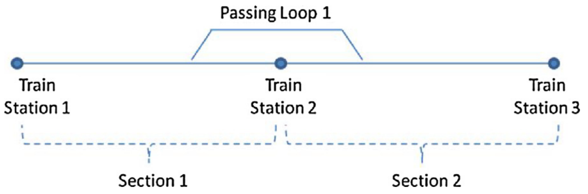

**Fig. 1.** Elements of a single-line rail system.

Some rail networks contain many parallel train tracks ("double-line sections", or "triple-line sections"), through which trains may cross each other simultaneously, and significant rail yard capacity may exist at intermediate stations (where trains can stop and wait for others to cross). In systems with such flexible rail infrastructure, users may resort to using discrete event simulation- and/or rule-based scheduling tools, since conflicts between train schedules can be easily managed on a station-to-station basis.

Other rail systems, however, have limited scheduling flexibility. This may occur when there are long single-line sections interspersed with double-line sections. Scheduling trains in these systems becomes particularly challenging when the system is shared by a combination of freight and passenger trains ("mixed-use" rail system) with very different train lengths, travel times and passing priorities, as well as various passing loop lengths which can accommodate different train sizes. The formulation presented in this paper addresses rail systems with limited-flexibility environments, considering all of the previously mentioned complexities.

### 1.3. *Current rail system design and operations best practices*

This section illustrates current industry best practices in determining rail system capacity and some strategies for rail system design. The model proposed in this paper allows a fresh approach to increasing business value in both operating existing rail systems or designing expansions for new rail systems.

A rail system comprises a number of different interdependent components, as illustrated in Fig. 2. Rail system capacity and demand are typically represented as (time) "slots" or (train travel) "paths". Demand is expressed as a quantity of required slots and infrastructure capacity is represented by available slots. To accommodate increased transportation capacity demand, two strategies are typically used: (1) reducing the number of required time slots by lengthening trains and smoothing demand, or (2) increasing the number of available slots by adding passing loops, doubling/tripling rail tracks on bottleneck segments, or by improving operations. The latter can be achieved, for example, by implementing more advanced train control technology, which enables shorter crossing times and therefore additional train slots (at the cost of increased capital expenditure).

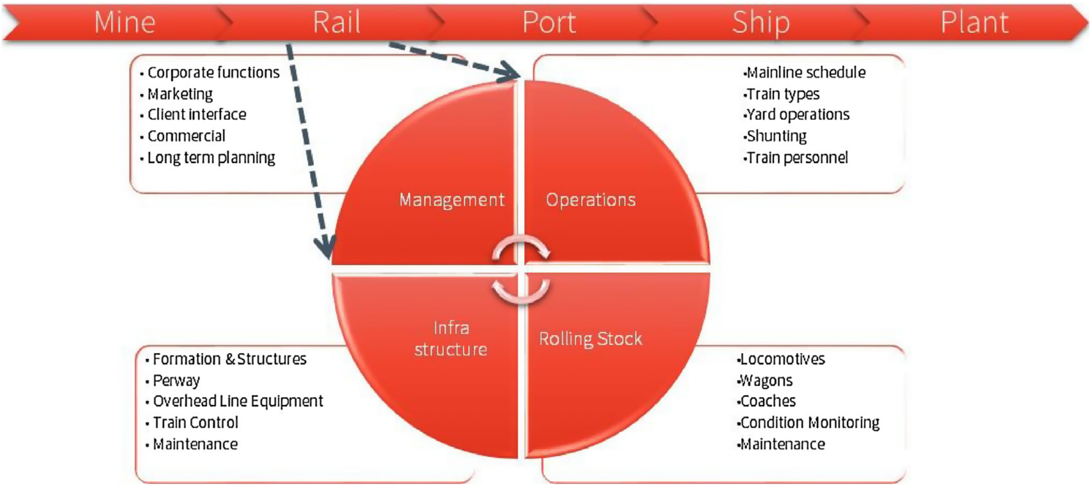

**Fig. 2.** Rail system components.

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